An astrophysical oscillator strength for the SII 94.7 nm resonance line and S abundances in DLAs . *

Piercarlo Bonifacio[1], Elisabetta Caffau[2], Miriam Centurión [1], Paolo Molaro [1], Giovanni Vladilo [1]

[1] *Osservatorio Astronomico di Trieste,Via G.B.Tiepolo 11, I-34131 Trieste, Italy*
[2] *Istituto Magistrale S.P.P. e L. annesso al Convitto Nazionale Paolo Diacono, S. Pietro al Natisone Udine, Italia*

ABSTRACT

By using UV spectra for the O star HD 93521 taken with the ORFEUS II echelle spectrograph, we determine an "astrophysical" f value for the SII $\lambda 94.7$ nm line: $f = 0.00498^{+0.00172}_{-0.00138}$, error at 1 σ level. This is almost a factor of 30 smaller than the guessed value found in the Kurucz database ($f = 0.1472$), which was up to now the only one available for this transition. We use our "astrophysical" f to investigate the S abundance in two Damped Lyα absorption systems (DLAs) observed with UVES at the ESO 8.2m Kueyen telescope. In the case of the absorber at $z_{abs} = 3.02486$ towards QSO 0347-3819 we find a sulphur column density which is consistent, within errors, with that determined by Centurión et al by means of the $\lambda 125.9$ nm line, thus providing an external check on the accuracy of our f value. For the damped absorber at $z_{abs} = 4.4680$ towards BR J0307-4945 we determine a high value of the S abundance, which, however, is probably the result of blending with Lyα forest lines.

Key words: 02.01.3-atomic data ; 09.01.2 ISM: abundances ; 11.17.1 quasars: absorption lines; 11.17.3 quasars: individual QSO 0347-3819 ; 11.17.3 quasars: individual BR J0307-4945 ; 08.09.2 Stars: individual HD 93521

1 INTRODUCTION

In the chemical study of DLAs the importance of S is twofold: first it traces the α elements, which are synthesized mainly by Type II SNe, so that the α/iron–peak ratio provides an important constraint on the chemical history of the observed material, and second S is known to be essentially undepleted onto dust grains (Savage & Sembach 1996), at variance with what happens for Si, which is the α element most commonly observed in DLAs. Therefore the S abundance in the gas phase measures the actual S abundance in the system (Centurión et al 2000). In the spectrum of BR J0307-4945, obtained with UVES on the ESO-Kueyen 8.2 m telescope during the commissioning of the instrument, a DLA at $z_{abs} = 4.4680$ is observed. For this system the SII triplet lines at 125 nm, which are the only ones used so far to determine the abundances of this nucleosynthetically important element (Centurión et al 2000), are not available because they are blended with lower redshift Lyα absorbers.

We have been able to detect the SII $\lambda 94.7$ nm resonance line for which, unfortunately, no theoretical or experimental f value is available, thus preventing its use in the analysis. The presence of the SII $\lambda 94.7$ nm line and the lack of a suitable f value are tantalizing.

The observations with the echelle spectrograph on board of the ORFEUS II mission allow to observe the SII $\lambda 94.7$ nm line in the Galactic interstellar medium with both a resolution and signal to noise ratio sufficient for its analysis. We therefore decided to use these data to derive an "astrophysical" f value for this transition. Our method is quite simple: we determine the f value by requiring that this line yields the same column density as the SII $\lambda 125$ nm triplet. The most suitable target for this analysis is the well known O star HD 93521. The SII $\lambda 94.7$ nm line has been clearly detected in its ORFEUS II echelle spectrum by Barnstedt et al (2000). In the present paper we perform a quantitative analysis on this feature. The ORFEUS spectrum covers both the SII $\lambda 94.7$ nm line and the SII $\lambda 125$ nm triplet. In order to support our analysis we also make use of archival data from IUE and HST-GHRS both of which contain information on the SII $\lambda 125$ nm triplet.

* based on data from the ORFEUS II mission, the Hubble Space Telescope, the International Ultraviolet Explorer and the ESO Very Large Telescope
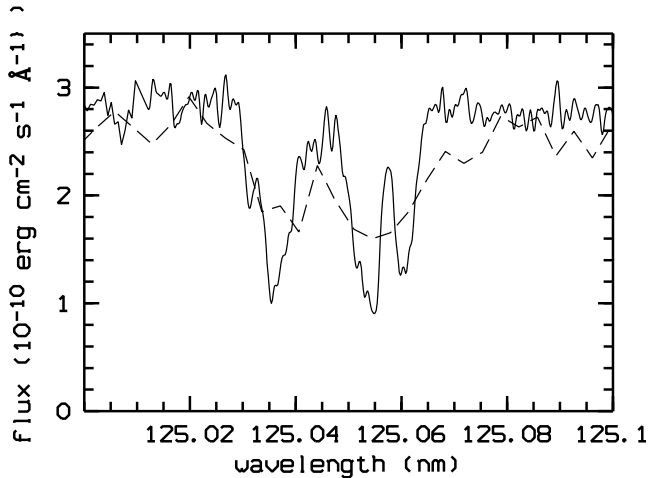
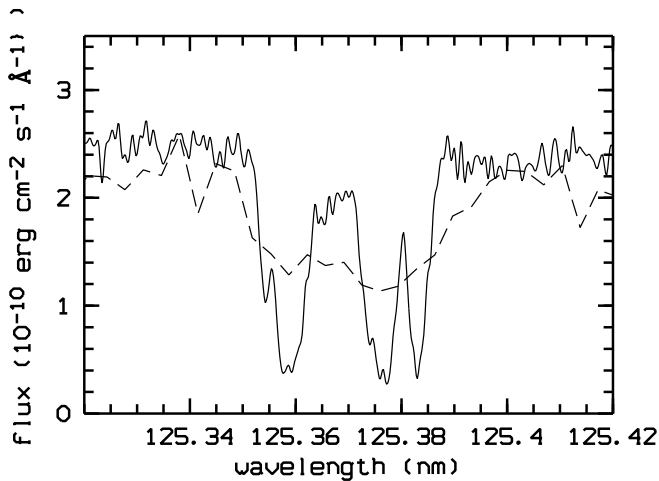**Figure 1.** The SII λ125.0 nm line with HST (solid line) and ORFEUS (dashed line).

Figure 2. The SIIλ125.4 nm line with HST (solid line) and OR-FEUS (dashed line).

2   OBSERVATIONAL MATERIAL

Our data consist of two echelle spectra from the ORFEUS II mission, three echelle spectra observed with the GHRS on board the HST. We also used 128 high resolution large aperture SWP IUE spectra.

The ORFEUS data under study here were described in detail by Barnstedt et al (2000) and instrument description, performance and data reduction by Barnstedt et al (1999). The wavelength coverage ranges from about 91.6 nm to 141.0 nm with a resolution of $\lambda/\Delta\lambda \approx 10000$. Each ORFEUS echelle spectrum consists of 22 echelle orders. We focussed on order 44 (125.421 nm – 128.457 nm), order 45 (122.635 nm – 125.602 nm) and order 59 (93.500 nm – 95.999 nm). Orders 44 and 45 contain the SII λ125 nm triplet while order 59 contains the SII λ94.7 nm line. The ORFEUS data was kindly provided to us by Dr. Kappelmann.

HST data consist of three GHRS echelle spectra, taken with the small science aperture (z0ih020ft, z0ih020gt, z0ih020ht), which we added without any wavelength shift. For each spectrum the resolution is $\lambda/\Delta\lambda \approx 85000$ and the
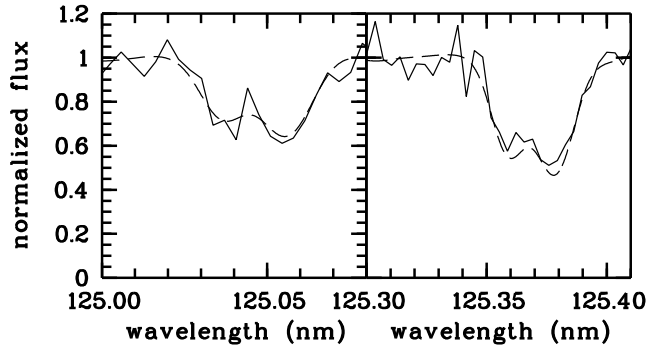

Figure 3. Normalized flux of ORFEUS (solid line) and HST (dashed line) of two of the SII λ125 nm triplet lines. The HST data have been broadened to the resolution of ORFEUS and shifted in wavelength to match the 125.4 nm line which lie in order 45.

exposure time is 144 s. These spectra were already analyzed by Spitzer & Fitzpatrick (1993).

The UVES spectra of the QSOs BR J0307-4945 and 0347-3819 were obtained during the commissioning of the instrument and released by ESO for public use. In the present paper we use one spectrum of BR J0307-4945 taken in the red arm centered at 600 nm with CD #3 and a 1$''$1 slit and an exposure time of 4400 s. For QSO 0347-3819 we use the sum of two blue arm spectra, for a total exposure time of 9500 s taken with dichroic #2 and centered at 437 nm CD #2 and a 1$''$0 slit. The reduced spectra were provided to us by Dr. M. Dessauges-Zavadsky and Dr. S. D'Odorico who used the UVES data reduction pipeline. Further details on the data reduction may be found in Dessauges-Zavadsky et al (2001) and D'Odorico et al (2001). The resolution is about 40000 for both spectra with S/N $\sim$ 40 in the regions under analysis here.

3   ANALYSIS AND RESULTS

Since HD 93521 is a fast rotator ($v \sin i = 400 \pm 25$ kms^{-1}, Lennon et al 1991) all stellar lines are very broad and it is therefore relatively easy to draw a local continuum relative to which the interstellar line may be measured. When we refer to "lines" in the following discussion we always mean the interstellar lines.

Due to the differences in resolution we could not compare HST data with ORFEUS spectra directly. Even the wavelength scale of the two instruments is not in agreement, as may be appreciated in figures 1–2. By least squares fitting we determined the wavelength shift and broadening to be applied to HST spectra in order to obtain the best agreement with the ORFEUS spectrum. In Fig.3 the degraded HST normalized spectrum is compared to the corresponding ORFEUS spectrum. The spectra have been normalized by fitting a spline through selected continuum points.

Although the HST full resolution spectra show the presence of 9 separate components (Spitzer & Fitzpatrick 1993), at the resolution of ORFEUS only two components are apparent, indicated hereafter as B (blue) and R (red) component. We fitted Voigt profiles to the spectra of the two instruments by using least squares in order to obtain the column density, the b value and the mean velocity of the

Table 1. Atomic data

$\lambda_\circ$ nm	f	g_1	g_2	ref
94.6978	0.00498	4.0	4.0	this paper
125.0584	0.00545	4.0	2.0	Morton 1991
125.3811	0.01088	4.0	4.0	Morton 1991
125.9519	0.01624	4.0	6.0	Morton 1991

Table 2. Best fit parameters for the SII 125 nm triplet

line	N Blue	b	N Red	b	Δv (kms^{-1})
ORFEUS					
125.0	14.91	10.52	15.02	13.05	-45.52
	± 0.09	± 2.5	± 0.07	± 3.0	± 1.0
125.4	14.91	6.10	15.02	17.03	-45.52
	± 0.09	± 2.0	± 0.07	± 7.0	± 1.0
125.9	14.91	10.52	15.02	13.05	-47.22
	± 0.09	± 2.5	± 0.07	± 3.0	± 1.0
HST					
125.	14.86	12.14	15.03	17.27	-45.84
	± 0.01	± 1.0	± 0.01	± 1.4	± 0.1

two components of each line of the SII $\lambda 125$ nm triplet. The atomic data for the transitions under study are summarized in Table 1. The results of the fits are given in Table 2.

A similar exercise was performed also using IUE data, for which we coadded 128 IUE large aperture SWP spectra. The flux of these spectra appeared in disagreement with that of both ORFEUS and HST. We believe this is due to the well known problems of background subtraction in IUE at these short wavelengths. We thus did not further consider the IUE spectrum.

Using the column density, the b parameter and the mean velocity for the B and R component of the best fit to the triplet lines we fitted the whole range from 94.6680 nm to 94.7120 nm in order to determine the f value of the S II $\lambda 94.7$ nm line.

We performed the fitting starting with the input parameters deduced from ORFEUS and HST in turn. The R component of the SII 94.7 nm line is blended with the H_2 $\lambda 94.6986$ nm line. For the H_2 lines we fixed $b = 7$ kms^{-1}, as found for all other H_2 lines by Gringel et al (2000), while we left the column densities as fitting parameters. For what pertains to the SII $\lambda 94.7$ nm lines all the parameters where kept fixed except the f value. Therefore we had three fitting parameters and 12 degrees of freedom; the results are reported in Table 2.

Taking as input the column densities derived from the ORFEUS data the fitted oscillator strength of the S II $\lambda 94.7$ nm line is

$$f = 0.00498^{+0.00172}_{-0.00138}$$

The fit is shown in Fig. 4. The quoted error is the 1σ de-
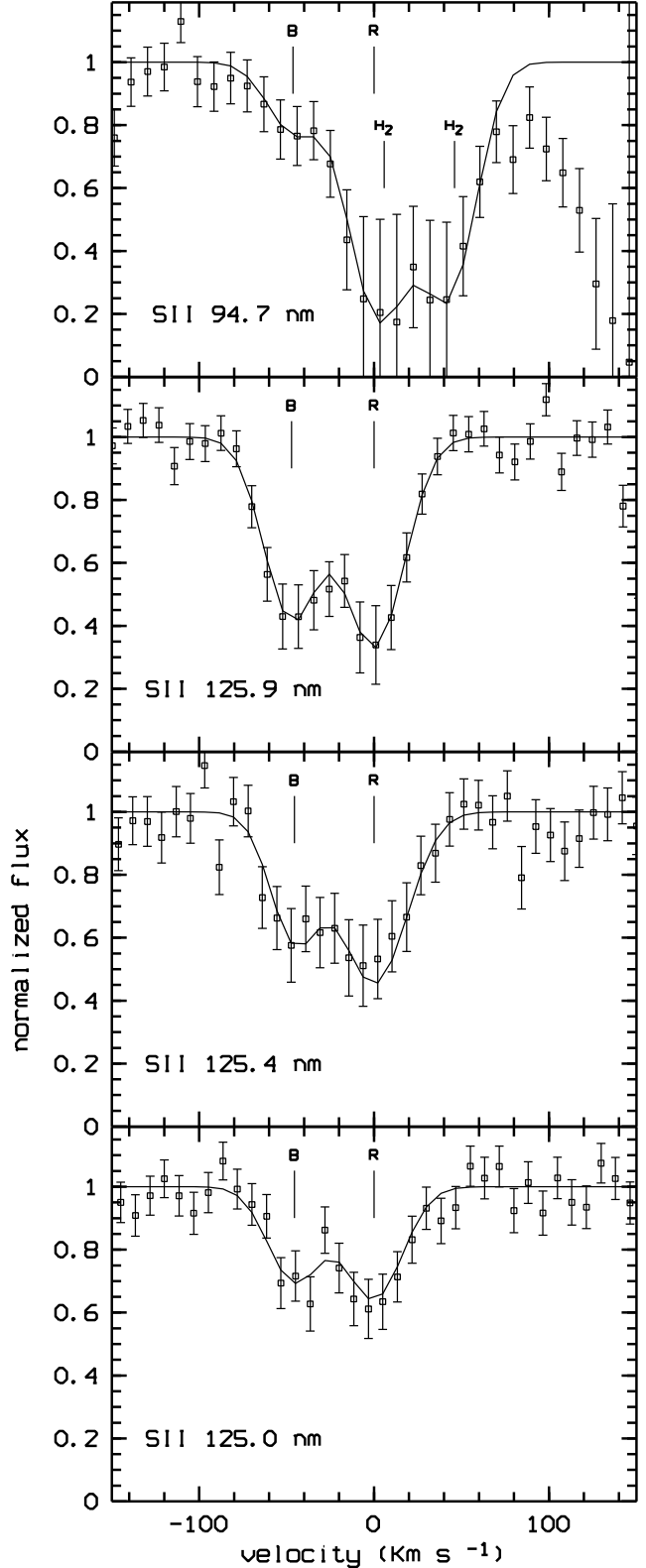

Figure 4. The synthetic spectra of the SII lines are over imposed to the data (squares with error bars). B and R identify the center of the blue ($v = -47$ kms^{-1}) and red ($v = 0$ kms^{-1}) components. In the top panel also the two H_2 blending lines are indicated.
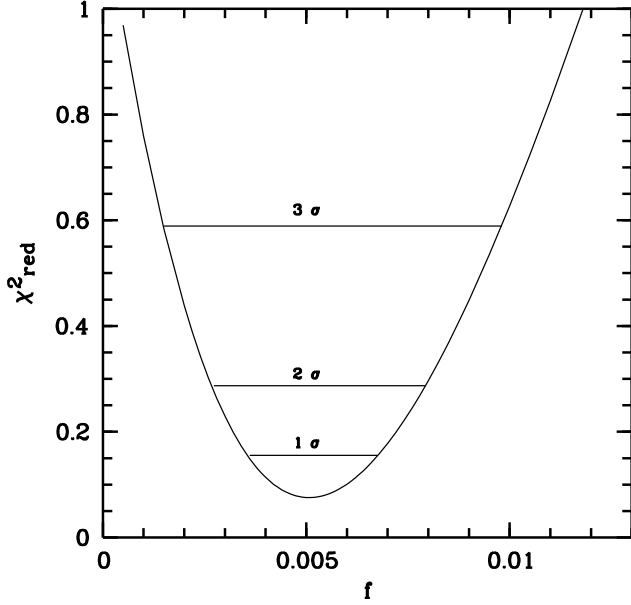
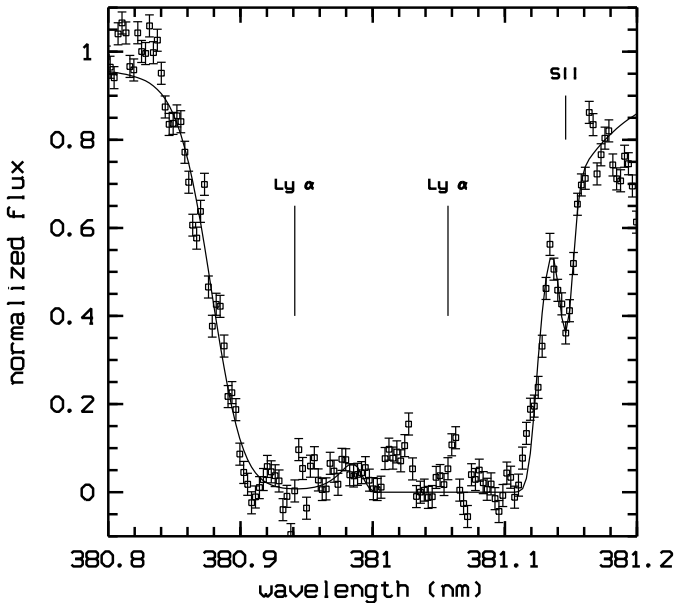**Figure 5.** The reduced χ^2 as a function of f.

Figure 6. UVES spectrum of 0347-3819: the SII 94.7 nm line of the absorption system at z_{abs} 3.02486, is clearly blended with Lyα absorbers of lower redshift; the continuous line is our best fit to the data.

duced from the χ^2 analysis, as shown in Fig.5. The oscillator strength found by using the column density deduced from HST data is $f = 0.00528^{+0.00157}_{-0.00148}$, in good agreement with that obtained above by using the ORFEUS–based column density.

4   APPLICATION TO THE STUDY OF QSO 0347-3819

The line–of–sight towards QSO 0347-3819 is characterized by the presence of one damped Lyα system with two com-

ponents very close to each other. The HI column density has been derived by Pettini et al (1994), while the SII column density has been measured from the $\lambda 125.9$ nm line by Centurión et al (1998), Ledoux et al (1998) and Prochaska & Wolfe (1999). The measurements of Centurión et al (1998) and Prochaska & Wolfe (1999) agree with each other, within errors, while the value of Ledoux et al (1998) is lower by $\sim$ 0.3 dex. We used the UVES spectrum of this QSO to provide an external check on the accuracy of our f value, namely by comparing the column density derived by the $\lambda 94.7$ nm line with the values of Centurión et al (1998) and Prochaska & Wolfe (1999). In Fig. 6 we show the observed spectrum together with our best fit. The SII $\lambda 94.7$ nm line falls on the wing of a Lyα absorber of lower redshift and this needs to be taken into account when modeling the line. We fit the feature successfully using two Lyα clouds and one SII $\lambda 94.7$ nm line, as shown in the figure. The fitted parameters are $\log N(\text{SII}) = 14.71 \pm 0.04$, $b = 3.4 \pm 1.0$. Another possible choice is to fit only the red wing of the feature by using one Lyα in this case we obtain $\log N(\text{SII}) = 14.70 \pm 0.04$, the redshift is $z = 3.024866$, $b = 3.1 \pm 1.0$ kms^{-1}. Both the values of the column density found are in perfect concordance, within errors, with the value of Centurión et al (1998): $\log N(\text{SII}) = 14.77 \pm 0.08$ derived from CASPEC spectra using Voigt profile fitting, as we do. They also agree with the value of Prochaska & Wolfe (1999): $\log N(\text{SII}) = 14.731 \pm 0.012$ derived from Keck HIRES spectra using the apparent optical depth method. Our b value is very small when compared with $b = 17.9 \pm 3.3$ kms^{-1} found by Centurión et al (1998). One should note however two facts: in the first place Centurión et al (1998) had a resolution of 15.4 kms^{-1}, to be compared with 7.1 kms^{-1} of the present data; in the second place, because of the lower resolution Centurión et al could not resolve the two components at $z_{abs} = 3.02466$ and $z_{abs} = 3.02486$ but fitted a single component with $z_{abs} = 3.02476$, i.e. the sum of the two. In the UVES spectra the two components are separated as may be appreciated by inspecting several transitions, however for the $\lambda 94.7$ nm line the bluemost component falls in the Lyα absorption and is not detectable. Therefore our column density refers to the $z_{abs} = 3.02486$ system only, while the value Centurión et al refers to the sum of both. It is thus not surprising that our column density is slightly *lower* than that of Centurión et al. The agreement of our new measurement with those of Centurión et al (1998) and Prochaska & Wolfe (1999), makes it unlikely that the abundance found by Ledoux et al (1998) is the correct one.

To test the influence of the adopted f on the derived column density we performed fits using the two extreme values given in the first row of Table 4. For $f = 0.00670$ we obtain $\log N(\text{SII}) = 14.57 \pm 0.04$, for $f = 0.00360$ we obtain $\log N(\text{SII}) = 15.11 \pm 0.04$. The fact that both values are in stark disagreement with the column density of Centurión et al (1998) suggests that the f value is more accurate than the formal 1σ errors derived from the χ^2 analysis.

5   APPLICATION TO THE STUDY OF BR J0307-4945

This high redshift QSO ($z_{em} = 4.74$) shows in its spectrum the DLA at highest redshift so–far known: $z_{abs} = 4.466$. This

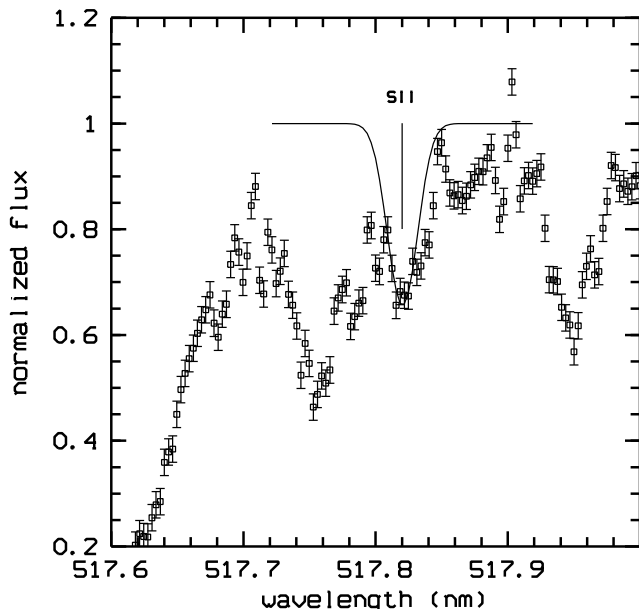**Figure 7.** UVES spectrum of BR J0307-4945: the SII λ94.7 nm line of the absorption system at z_{abs}4.4680; the continuous line is our best fit to the data.
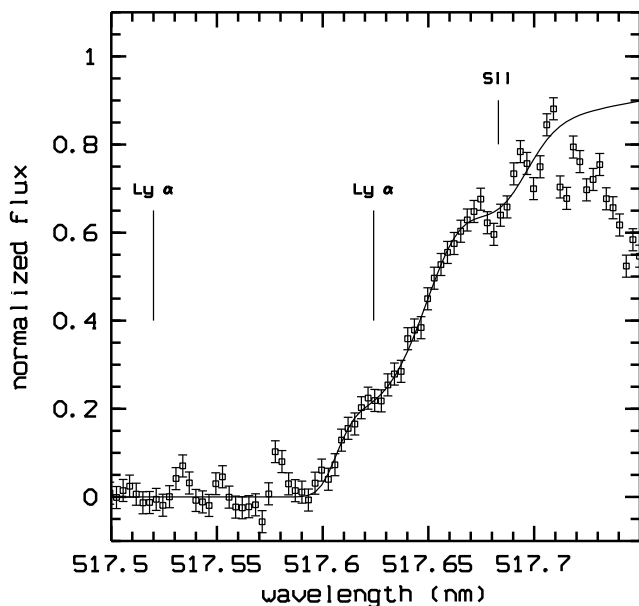

Figure 8. UVES spectrum of BR J0307-4945: the SII 94.7 nm line of the absorption system at z_{abs}4.4666, is blended with lower redshift Lyα absorbers; the continuous line is the our best fit to the data, we modeled the Lyα absorption assuming two components.

very complex system, for which no less than 14 separate components are required to describe the low–ions, is studied in detail by Dessauges-Zavadsky et al (2001). We identify the SII λ94.7 nm line at z_{abs}= 4.4666 (component # 8) and at z_{abs}= 4.4680 (component # 13), which are the main components of the system.

The SII λ94.7 nm line at z_{abs}= 4.4680 is relatively blend-free, although there is clearly some extra-absorption on the red wing. The fitted parameters are log N (SII) = 14.72 ±

0.07, $b = 7.7 \pm 2.0$ and redshift $z = 4.4681$, the fit is shown in Fig. 7. The sulphur abundance for this system, which has log N(HI) = 20.56 (Dessauges-Zavadsky et al 2001), is therefore [S/H]= $-1.04^{\dagger}$, which is consistent with the upper limit given by Dessauges-Zavadsky et al ([S/H]< -0.41). By combining our measure of S column density, with the column densities of Dessauges-Zavadsky et al for O, Si and Fe we obtain: [S/O]= +0.68, [S/Si]= +0.94 and [S/Fe]= +1.33. The above abundance ratios are very peculiar. Non solar S to α element ratios are not theoretically excluded, although observationally this would be the first occurence of such a case. Most likely the line could be contaminated by a Lyα, in which case our measure should be considered as an upper limit to the S abundance.

The line of the z_{abs}= 4.4666 system is blended with Lyα absorbers of lower redshift. We obtain a reasonable fit corresponding to log N (SII) = 14.47 ± 0.26, $b = 10.3 \pm 3.9$ and redshift $z = 4.4667$. The result depends strongly on the modeling of the Lyα absorption, therefore, although the fitted redshift is in good agreement with that of component # 8 of Dessauges-Zavadsky et al (2001), we consider this as a tentative identification.

6 CONCLUSIONS

By requiring that the SII λ94.7 nm line and the SII λ125 nm triplet provide the same SII column density in the line of sight towards HD 93521 we have been able to deduce an "astrophysical" f value for the SII λ94.7 nm line. The error, of the order of 30%, is essentially associated to the noise present in the spectra. As an external check of the accuracy of our f value we used the SII λ94.7 nm at z_{abs}=3.02486 towards QSO 0347-3819 to determine the SII column density and were able to confirm, within errors, the value found from the λ125.9 nm line by Centurión et al (1998). This result gives us further confidence in our f value and suggests that the accuracy is better than these formal error estimates. We warn the readers that the value log $gf = -0.230$ listed for the SII λ94.7 nm in table 3 of Barnstedt et al (2000) is a guessed value which comes from the Kurucz (1993) database. This value is almost a factor of 30 larger than our "astrophysical" value (log $gf = -1.70$) and should not be used in sulphur abundance analysis.

As an application we derived the SII column density in the absorption system at z_{abs}= 4.4680 towards BR J0307-4945. In this system the S column density cannot be derived from the λ125 nm triplet because of blending with Lyα clouds. The high [S/O] ratio implied by our measurement has no straightforward explanation, which suggests that the line could contaminated.

$\dagger$ we use here the usual notation: [X/Y] = log(X/Y)−log(X/Y)$_{\odot}$.

REFERENCES

Barnstedt J., Kappelmann N., Appenzeller I., Fromm A., Gölz M., Grewing M., Gringel W., Haas C., Hopfensitz W., Krämer G., Krautter J., Lindenberger A., Mandel H., Widmann H., 1999, A&AS, 134, 561

Barnstedt J., Gringel W., Kappelmann N., Grewing M., 2000, A&AS, 143, 193

Centurión, M., Bonifacio P., Molaro P., Vladilo G., 2000, ApJ, 536, 540

Centurión, M., Bonifacio P., Molaro P., Vladilo G., 1998, ApJ, 509, 620

Dessauges-Zavadsky M., D'Odorico S., McMahon R.G., Molaro P., Ledoux C., Péroux C., Storrie-Lombardi L.J., 2001, A&A submitted

D'Odorico S., Dessauges-Zavadsky M., Molaro P., 2001, A&A submitted

Gringel W., Barnstedt J., de Boer K.S., Grewing M., Kappelmann N., Richter P., 2000 A&A 358, L37

Kurucz R.L. , 1993, CD-ROM n. 18, Smithsonian Astrophysical Observatory, http://cfaku5.harvard.edu/LINELISTS.html

Ledoux C., Petitjean P., Bergeron J., Wampler E.J., Srianand R., 1998, A&A 337, 51

Lennon D.J., Dufton P.L., Keenan F.P., Holmgren D.E., 1991, A&A 246, 175

Morton D.C., 1991, ApJS, 77, 119

Pettini M., Smith L.J., Hunstead R.W., King D.L., 1994 ApJ, 426 79

Prochaska J.X., Wolfe A.M., 1999, ApJS, 121, 369

Savage , Sembach , 1996, ARA&A, 34 279

Spitzer L. Jr., Fitzpatrick E.L., 1993, ApJ, 409, 299

Vladilo G., Centurión M., Bonifacio P., Howk C., 2001 ApJ submitted